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Intensity Probe 02-20 Using Miniature Hollow Spheres

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Technical Report No. TR 03-001
January 2003

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Applied Research Laboratory

Applied Research Laboratory   *Penn State University*

20030221 070

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*
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1. REPORT DATE *(DD-MM-YYYY)* January 2003	2. REPORT TYPE Technical Report		3. DATES COVERED *(From - To)*
4. TITLE AND SUBTITLE Intensity Probe 02-20 Using Miniature Hollow Spheres			5a. CONTRACT NUMBER BOA N00014-00-G-0058/0024
			5b. GRANT NUMBER
			5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) David J. Van Tol, Gerald C. Lauchle, Thomas B. Gabrielson			5d. PROJECT NUMBER
			5e. TASK NUMBER
			5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Applied Research Laboratory The Pennsylvania State University P.O. Box 30 State College, PA 16804-0030			8. PERFORMING ORGANIZATION REPORT NUMBER TR 03-001
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research 800 North Quincy Street Arlington, VA 22217			10. SPONSOR/MONITOR'S ACRONYM(S)
			11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A: Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A probe is designed to measure the acoustic intensity at the primary frequencies (20-30 kHz) of a parametric array. It is designed to operate at depths up to 61 m with a pressure sensitivity of less than -235 dB re 1V/mPa while not disturbing the acoustic field of interest. Higher sensitivity would result in saturation when exposed to the expected sound pressure levels. The sensitivity and depth requirements were met, while the acoustic field disturbance issue is not yet fully resolved.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON David J. Van Tol
a. REPORT	b. ABSTRACT	c. THIS PAGE			
Unclassified	Unclassified	Unclassified	Unlimited	15	19b. TELEPHONE NUMBER *(include area code)* (814) 865-9589

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39-18

ABSTRACT

A probe is designed to measure the acoustic intensity at the primary frequencies (20-30 kHz) of a parametric array. It is designed to operate at depths up to 61 m with a pressure sensitivity of less than -235 dB re 1V/mPa while not disturbing the acoustic field of interest. Higher sensitivity would result in saturation when exposed to the expected sound pressure levels. The sensitivity and depth requirements were met, while the acoustic field disturbance issue is not yet fully resolved.

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INTRODUCTION

The Office of Naval Research (ONR) has supported research for a parametric array sonar for use in detecting mine-like objects in littoral water. As part of this effort, the Applied Research Lab at Penn State (ARL) is attempting to fully characterize the acoustic field from a parametric array. This involves measuring the acoustic intensity in order to determine the active and reactive power flow within the mixing region of the parametric sound field. These measurements should be performed at both the primary and secondary frequencies of the parametric source in question.

The parametric array under study has primary frequencies centered around 25 kHz, while the secondary frequency is 2 – 7 kHz. The intensity probe 02-20 described in this report is designed to measure the acoustic intensity at the primary frequencies.

Acoustic intensity measurements in water at frequencies near 25 kHz has not been reported. This report will describe the intensity probe that was created for this purpose and the performance of that probe.

SPECIFICATIONS

This device must accurately measure acoustic intensity in water at frequencies around 25 kHz. The acoustic field must not be disturbed by the existence of this probe. The sensitivity must be –235 dB re 1 V/μPa or lower to avoid saturation at the high sound pressure levels expected from the parametric source. And finally, it must do all this at depths of up to 61 m (200'). These specifications are summarized in Table 1.

Table 1. Specifications

Specification	Specified value
Frequency Range	20-30 kHz
Sensitivity	< -235 dB re V/μPa
Maximum Depth	61 m (600 kPa)

DESIGN

First, the issue of scattering must be examined. As mentioned in the specifications, the acoustic field must not be disturbed by the existence of the probe. The rule of thumb for meeting this requirement is a maximum dimension of $kD \leq 2$, as derived from [1]. The wave number k in water at 25 kHz is approximately 105 m^{-1}, so the size of the intensity probe D must be less than 19 mm.

The intensity probe uses the p-p technique, so named because it estimates intensity along an axis using two pressure measurements on that axis at a known separation distance. Considering the probe size requirement as listed above, the individual sensors must be much smaller than D (19 mm) to get point estimates of the pressure. The sensor chosen for this application is a hollow piezoelectric sphere [2, 3], also known as the BB for its similarity to the ammo from an air rifle.

The size of the spheres used in this probe is 0.9 mm diameter. These spheres are reported to survive pressures of at least 2.8 MPa (400 psi), equivalent to 280 m depth [4]. Some spheres survive pressures of up to 2.5 times higher than this.

Finally, the spacing of the pressure measurements must be determined. As described in [5], the error in the active intensity estimate is a function of the pressure sensor phase mismatch and the distance between the two sensors. This error is shown in Figure 1 for the active intensity of a plane traveling wave along the axis of the pressure sensors. Examining that figure, it is seen that the minimum error occurs in the region around $k\Delta r = 0.5$ for a typical phase mismatch of a few degrees. In water at 25 kHz, this means that the separation distance Δr should be 4.8 mm.
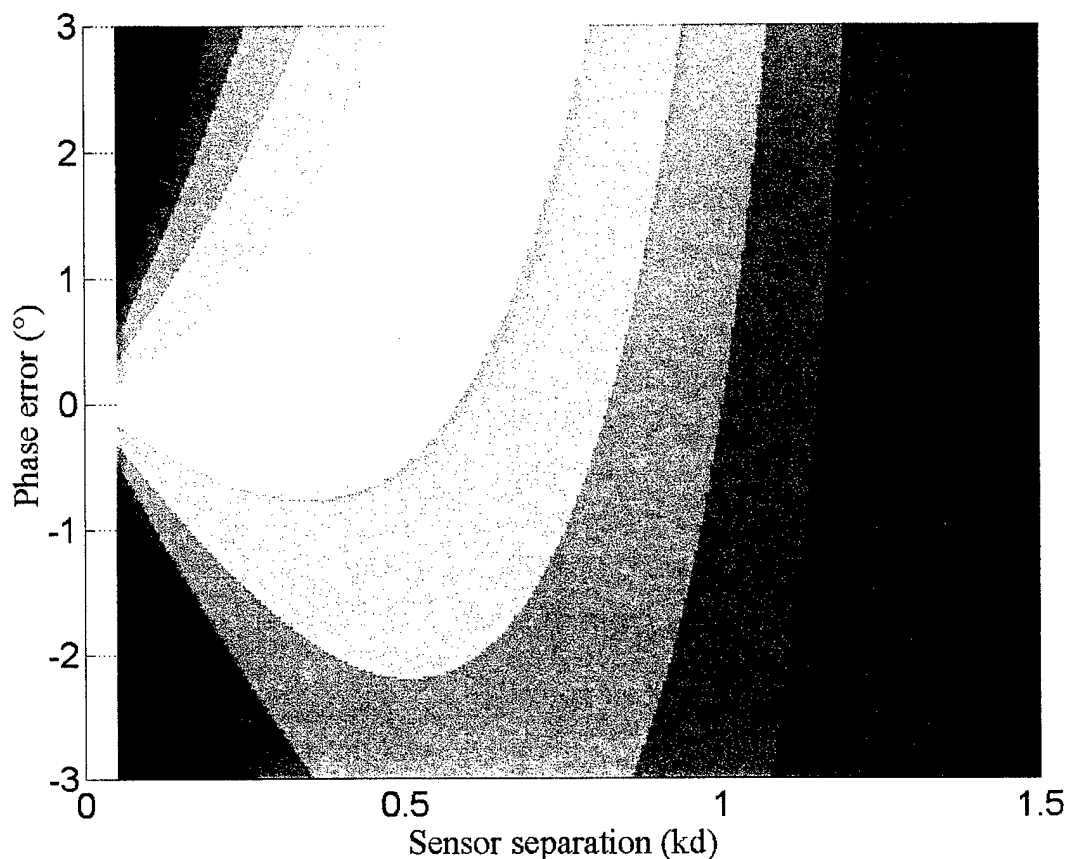

Figure 1: **Active intensity error of a plane wave along the axis of two pressure sensors in a p-p probe. The lightest area denotes an error of 0 - 0.5 dB, with the gray areas indicating increasing errors in steps of 0.5 dB.**

The basic parameters of the intensity probe are set. But there is one alternative to the common p-p probe that should give more accurate intensity estimates – a third pressure sensor. The three sensors are colinear, and the spacing between two adjacent sensors is 4.8 mm. The center element is used to estimate the pressure at the center of the probe, while the difference between the two outer sensors is used to estimate the velocity at the center of the probe. The derivation of the spectral intensity estimators and the advantages of this configuration are described in [5]. An added bonus is redundancy – if either of the outside sensors fails, the other two can still be used to measure intensity in the frequency range of interest.

Next the sensitivity specification of the transducers must be met. The intrinsic sensitivity of a 0.9 mm sphere is approximately –225 dB re 1 V/μPa, and the capacitance of the selected spheres is around 70 pF. This sensitivity needs to be reduced, and the easiest way to do so is capacitive loading. A cable needs to be incorporated from the sensor to the preamplifier, so that cable can be used to load the hydrophone to reach the target sensitivity of –235 dB re 1 V/μPa.

The sensitivity reduction can be estimated by the equation $M_0' = M_0 \dfrac{C_{hyd}}{C_{tot}}$, where M_o is the intrinsic sensitivity of the hydrophone in linear units, C_{hyd} is the intrinsic capacitance of the hydrophone, C_{tot} is the sum of the hydrophone and cable capacitance, and M_o' is the reduced sensitivity. Using the data from above, the cable capacitance must be about 150 pF. Assuming 100 pF/m for the cable, this gives a cable of 1.5 m long. To be on the safe side, this probe was built with a 3 m cable on each sensor, so the predicted sensitivity was –240 dB re 1 V/μPa.

On the topic of cable, an appropriate cable for the depth requirement is desired. An RG-174/U coaxial cable has the right size and conductor configuration, but is not rated for submerged use. A sample of this cable was sealed at one end and tested at 700 kPa (100 psi) for 4 hours without any measurable change in characteristic, and was thus deemed suitable for use. The actual capacitance of the RG-174/U is nominally 101 pF/m, which is appropriate for the sensitivity calculations shown in prior paragraphs.

CONSTRUCTION

The basic design of the probe is determined: three hollow spheres held in a line with 3 m of RG-174/U coaxial cable attached to each sphere. Now the construction method will be described.

The spheres must be held collinear in a structure that minimizes scattering of the acoustic field. Building that structure of polyurethane should help with the scattering issue since the acoustic impedance is a good match to water. And, of course, it needs to be small.

Start the construction with a mold as shown in Figure 2. Using Dow Corning Silastic J RTV, cast a negative mold around the entire piece. Using spheres with the cables attached, insert the spheres in each of the three wells that are at the bottom of that mold. Partially fill that mold with Epoxical CPD 9150 polyurethane. Figure 3 shows a picture of a prototype unit after this urethane has cured and the device was removed from the mold.

Now attach the aluminum mold from figure 2 to a 12.7 mm (½") diameter, 10 cm (4") long rod. Attach the aluminum mold to one flat end of the rod with the three bumps facing away from the rod. Align the center bump with the centerline of the rod. Again use the RTV to cast a negative mold of the entire piece. After the RTV has been cured, remove the male molds and cut the end of the negative mold to create an opening on both ends of the mold.

Pass the RG-174/U cables through this negative mold. Insert the rectangular block of polyurethane and the spheres into the end of the mold. Fill the rest of the mold with the same CPD 9150 polyurethane and cure.

The negative mold can now be removed. It must be cut away from the probe. Coat the spheres with a thin layer of the same polyurethane used in the rest of the process. The resulting probe is shown in Figure 4.
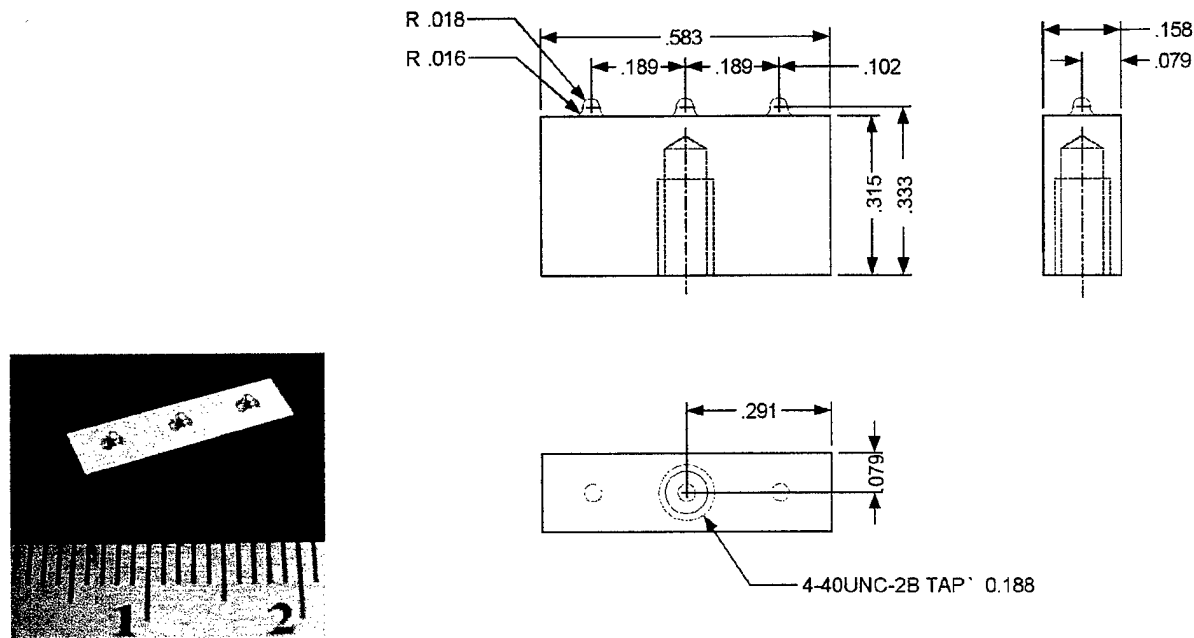

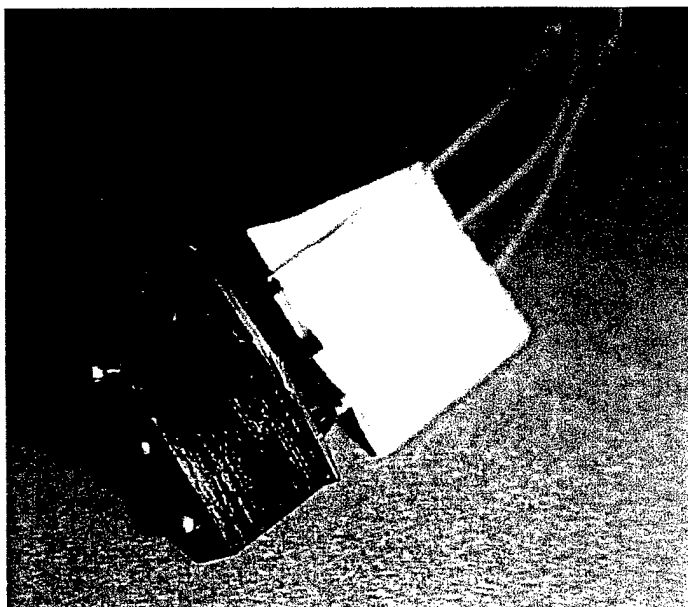**Figure 2: Picture (left) and drawing (right) of the mold**

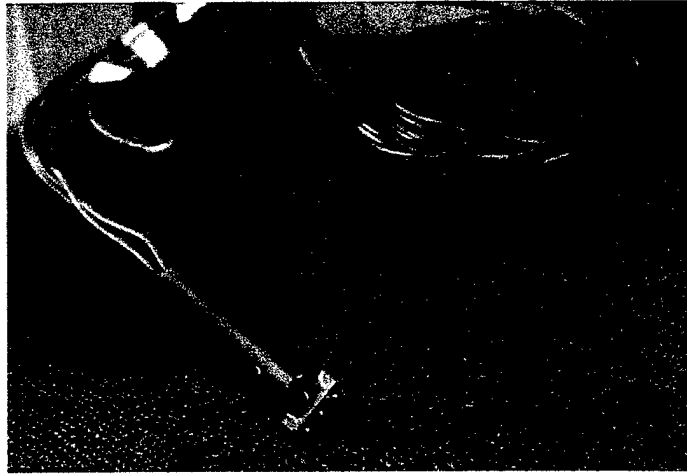**Figure 3: Prototype intensity probe after initial encapsulation step**

Figure 4: Fully assembled intensity probe

TESTING AND RESULTS

The testing was completed in two phases. First, it was subjected to an environmental test by exposing the probe to hydrostatic pressure and while monitoring the capacitance of the sensors. After that test was passed, the performance was evaluated through calibrations in the test tank. All of these tests were performed at the ARL.

Hydrostatic Pressure Tests

The intensity probe was placed in the 23" tube in the ARL high-pressure test facility. The cables exited the tube through cord grips so the capacitance of each sensor could be monitored. The pressure in the tube was cycled to 700 kPa (100 psi) for three periods of at least five-minute duration with at least minutes of atmospheric pressure in between. One four-hour period at 700 kPa followed.

The capacitance and dissipation of the sensors were monitored as well as the insulation resistance from the cable conductors to the metal pressure vessel. The results of this test are shown in Figures 5 and 6. Two of the sensors showed very little variation in parameters during these tests. One sensor showed greatly reduced insulation resistance at the end of the 4-hour cycle.
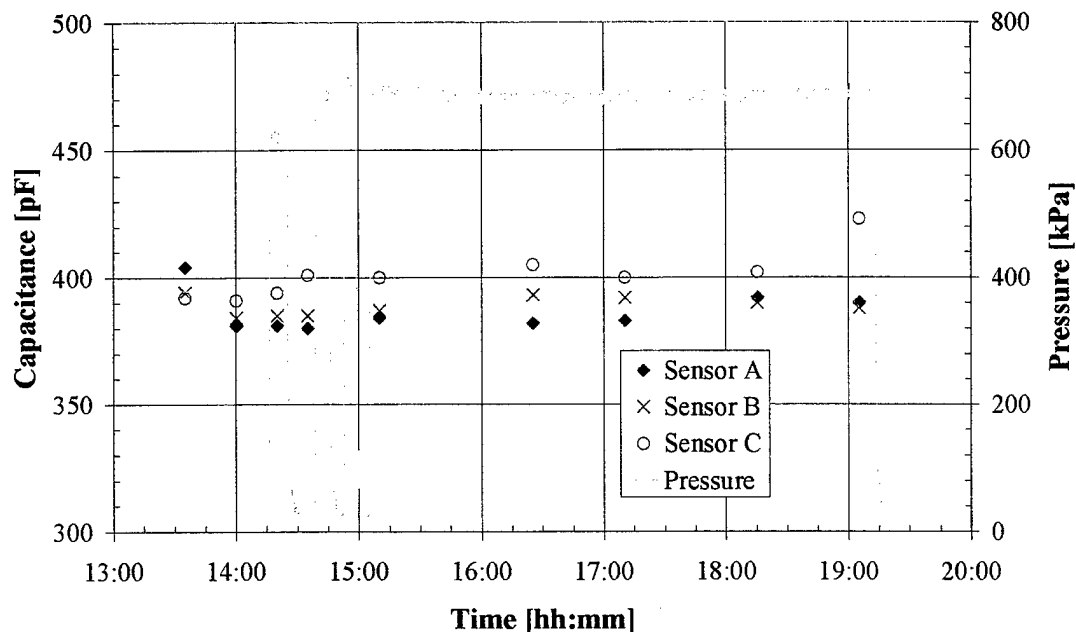
Figure 5: Capacitance as a function of time overlaid with the hydrostatic pressure
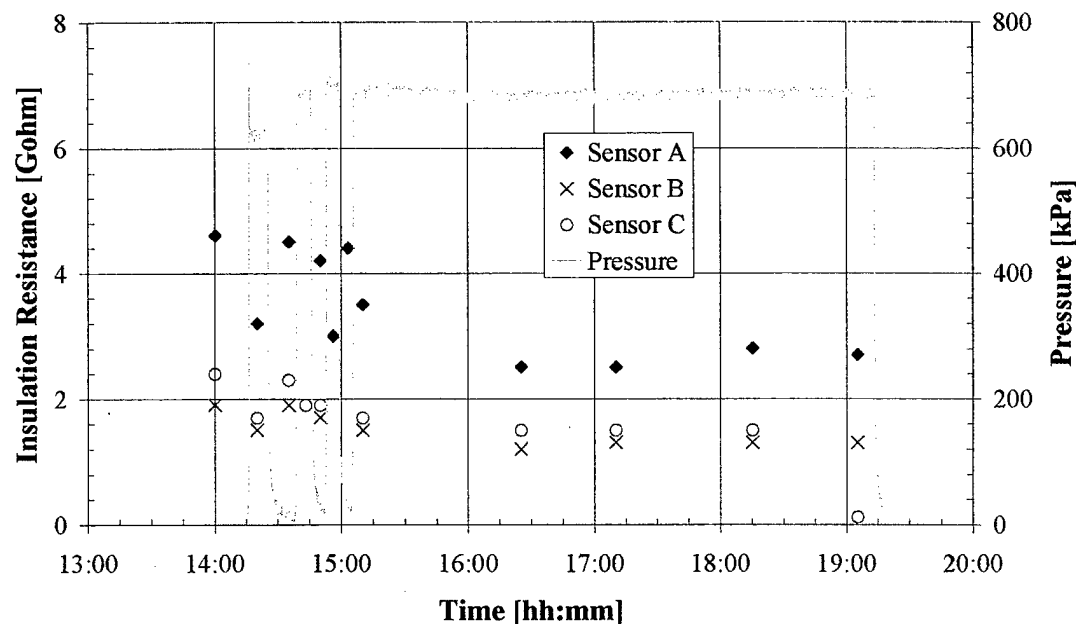

Figure 6: Insulation resistance as a function of time overlaid with the hydrostatic pressure

The reason for this change in sensor C was made obvious by inspection with a microscope. When applying the last coat of polyurethane over the spheres, a small bubble formed at the top of this sphere. The bubble was not visible to the naked eye. A small section of the sphere was missing, as shown in Figure 7. This may have been caused by the absence of waterproofing and the hydrostatic force acting on the sphere. The hole was sealed with more polyurethane and sensor C was deemed useless for the rest of the testing.
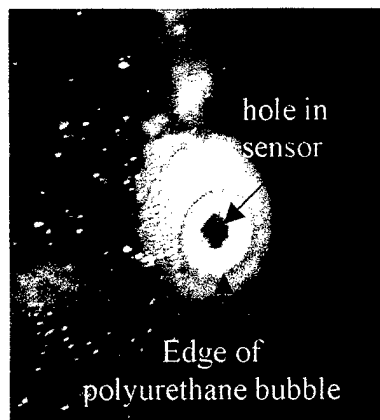
Figure 7: Sensor C with the missing segment (sensor is 0.9mm diameter, bubble is estimated 0.3 mm diameter)

Acoustic Testing

The acoustic performance of an intensity probe based on pressure sensors is indicated through two parameters. The first is sensor match in amplitude and phase, and the second is scattering caused by the probe.

Relative Sensitivity

Characterizing the sensitivity match is quite simple in principle. Expose both sensors to the same pressure field and measure the relative responses. The trick is to ensure that both sensors are in the same pressure field; positioning the sensors such that the phase of the pressure is exactly the same is difficult.

The technique commonly used [6] is to expose the pressure sensors to a given pressure field, then reverse the positions of the pressure sensors and repeat the test. If the positions are reversed accurately, any difference in pressure phase can be removed from the measurement. In the ARL anechoic tank facility, the field reversal is done by rotating the probe 180 degrees.

A hurdle to making this measurement came from an unlikely source: electrical crosstalk. Each sensor has an RG-174/U coaxial cable, 3 m long. When the probe was rotated 180 degrees and then returned to its original bearing angle, the relative phase measurements were not repeatable to within four degrees. After much experimentation, the movement of the cables and the changing crosstalk between the elements was determined to be the source of the problem. This problem was patched by taping the cables together such that they were not free to move independently. Now the crosstalk was constant, and repeatable measurements were possible. This crosstalk is a disturbing problem, and it is not known how it may affect intensity measurements.

The relative sensitivity of sensors A and B is shown in Figure 8, while the absolute sensitivities are shown in Figure 9. Over the frequency range of interest, 20-30 kHz, the amplitude mismatch is 2-3 dB and the phase mismatch is a few degrees. As seen in Figure 1, one degree of phase mismatch can cause significant reduction of the useful frequency range. So even though the

phase difference is quite small, intensity measurements will require compensation. The amplitude mismatch is certainly great enough to cause large errors in intensity measurements, so that must also be compensated.
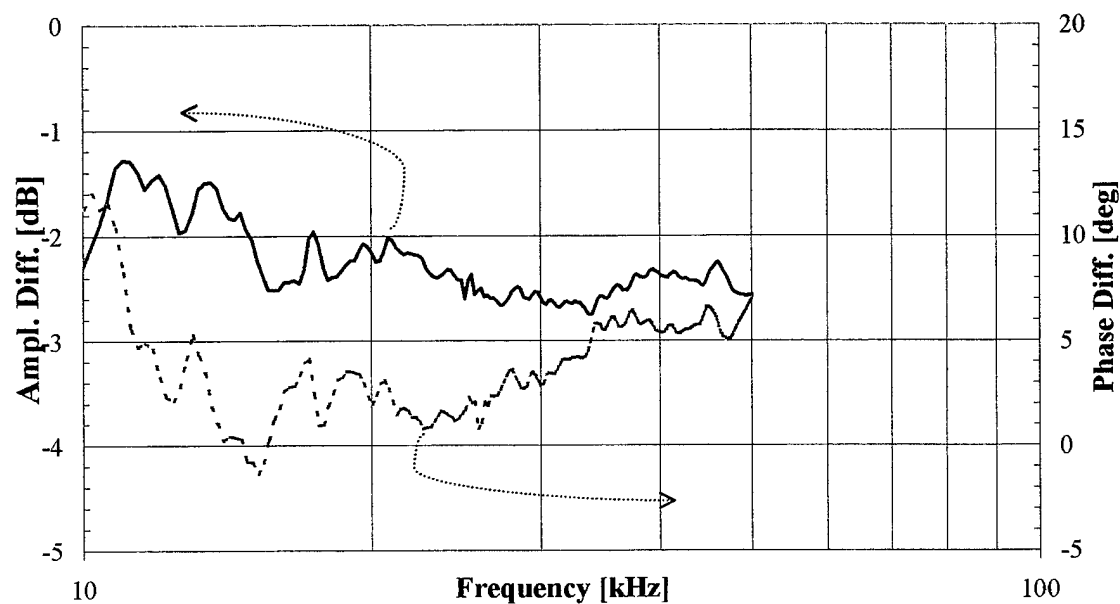

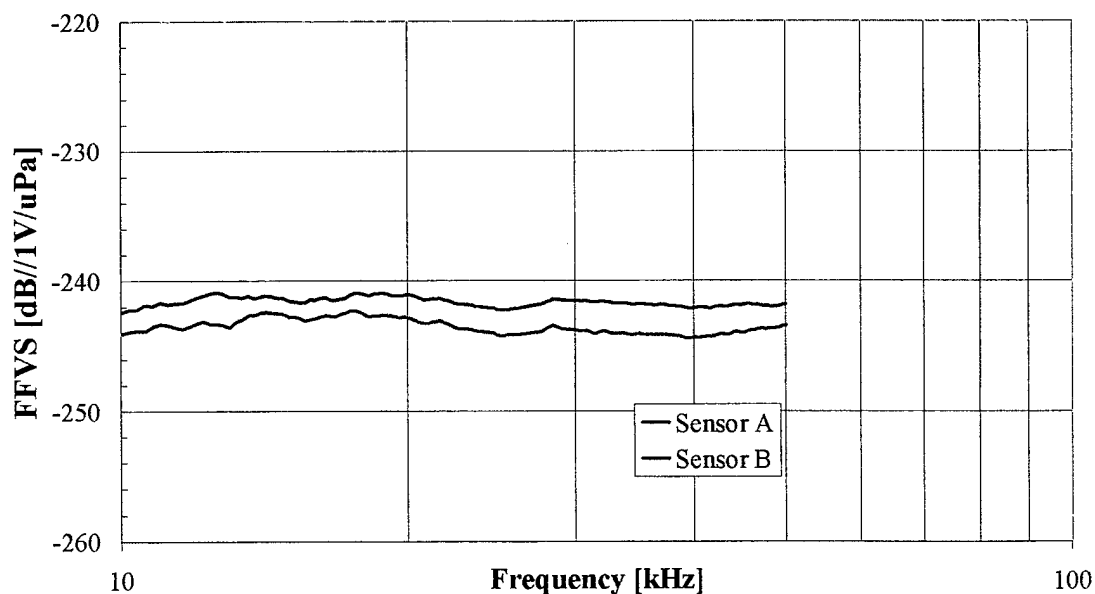**Figure 8: Relative sensitivity of sensors A and B**

Figure 9: Absolute sensitivity of sensors A and B

Scattering of the measured field

A quantified measurement of the acoustic scattering due to the existence of the probe has not yet been developed. One way to indicate the degree of scattering is to measure the pressure difference at different angles of incidence to the intensity probe.

The intensity probe 02-20 was rotated as acoustic pulses were sent from a stationary transducer. The pressure phase and amplitude at each sensor was measured. After the sensitivity mismatch was compensated, the difference between the pressure sensors was computed and is shown in Figure 10. The difference magnitude will ideally follow the cosine function, so the cosine function is shown in that figure for comparison.

Figure 10 shows some obvious differences from the theoretical ideal. That can be broken down a little further into phase and amplitude differences. Shown in Figure 11 is the phase difference between the two sensors at three frequencies as a function of bearing angle. These phase differences do not track the ideal sinusoid well, as is obvious from the figure. Looking at the 25 kHz data, for example, one can see that the phase maxima and minima (at approximately +/- 90° bearing, Figure 11) are not well matched. This is the primary contributor to the mismatch of the two lobes in the difference pattern at 25 kHz as seen in Figure 10.
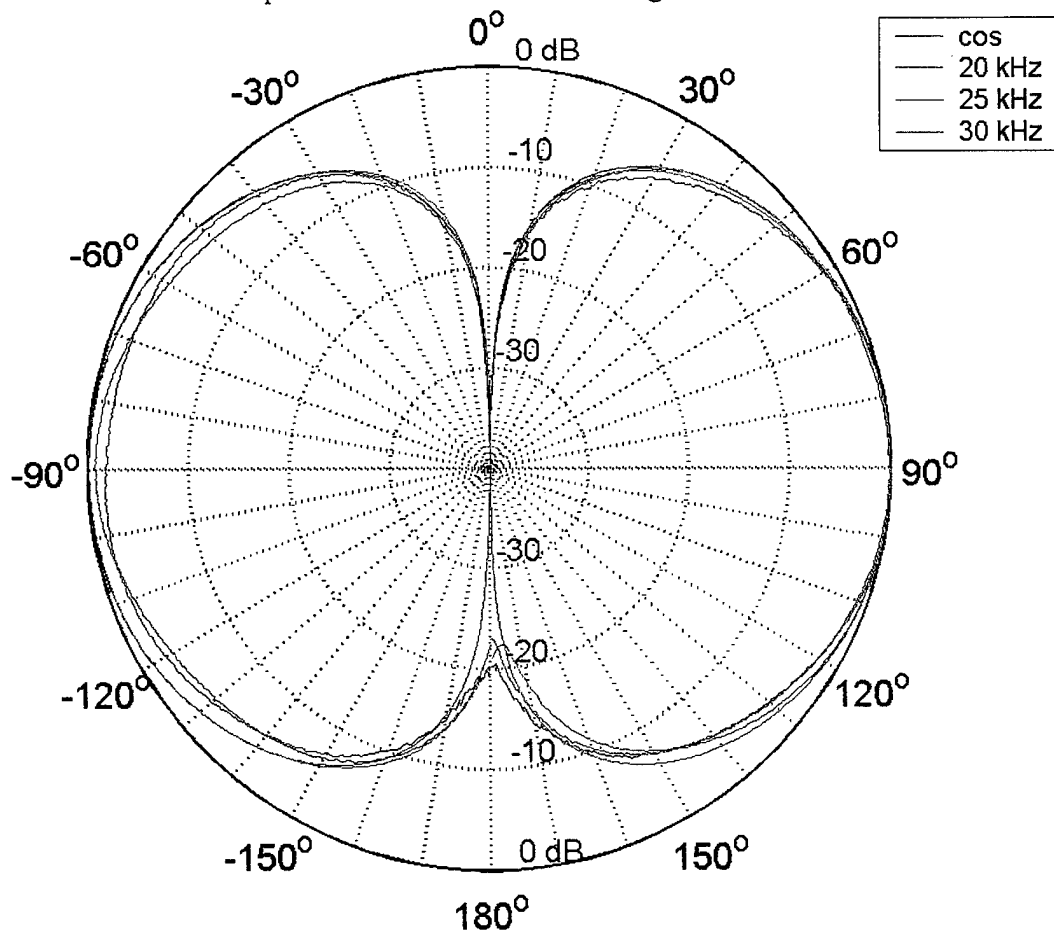

Figure 10: Pressure difference between two phase and amplitude compensated sensors in intensity probe 02-20 and the ideal cosine pattern
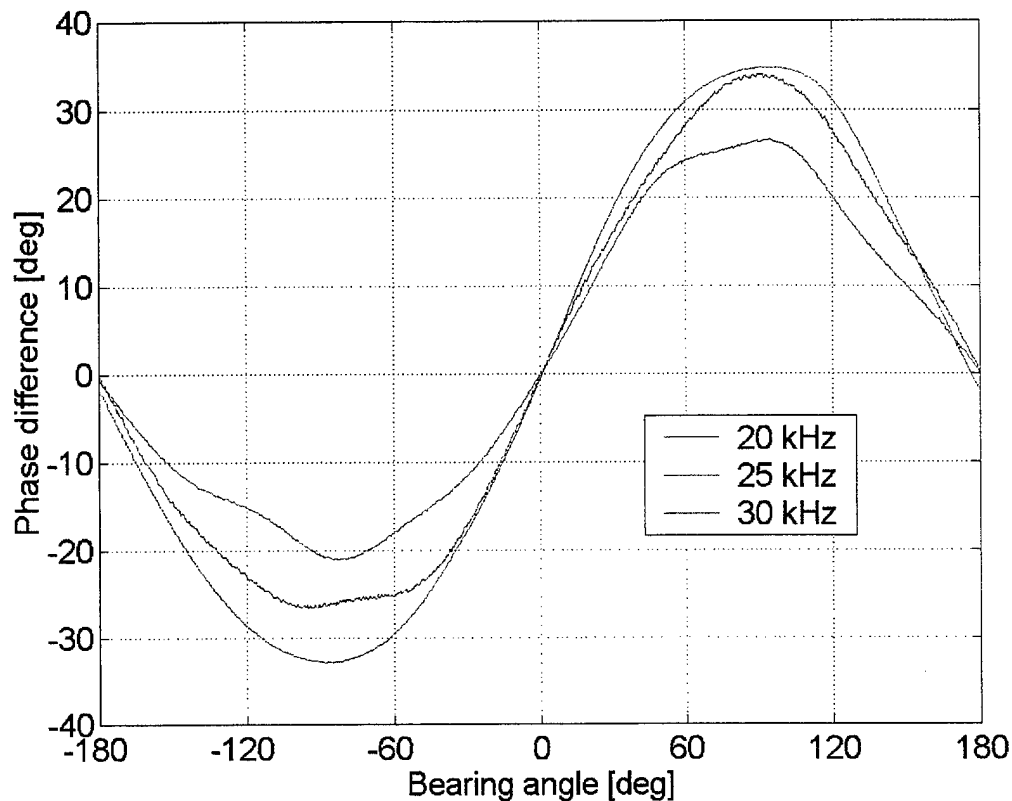
Figure 11: Phase difference between uncompensated sensors as a function of bearing angle and frequency

CONCLUSIONS

A three-pressure sensor intensity probe has been described. Two sensors meet the sensitivity specification, and the depth requirement. The third sensor was not evaluated after it failed the depth tests. A few conclusions regarding the sensitivity match and the scattering follow.

In Figure 8 the phase mismatch between the pressure sensors is seen to be 1-4 degrees in the 20-30 KHz band. From Figure 1, that phase mismatch results in up to 2 dB error in intensity measurement. So even though the phase difference is quite small by ordinary standards, intensity measurements will require compensation. The amplitude mismatch is certainly great enough to cause large errors in intensity measurements, so that must also be compensated. The correction factor for amplitude and phase can be a single number for the entire band. This simple correction will result in a mismatch of <0.5 dB and <2° phase at any frequency, resulting in intensity estimates with ≤ 1 dB error. This compensation process is expected with p-p intensity measurements, and rare is the probe that does not require compensation.

Examining Figure 10, the dipole patterns are not as clean as desired. While there is not a commonly accepted quantification of those dipole patterns, it is apparent that this probe has not reproduced dipole accurately. The most significant deviation from the ideal pattern is in the

asymmetry at 20 and 25 kHz. Figure 10 shows that the dipole pattern is close to the ideal on the right side (0 to 180 °), but the lobe on the left side (0 to −180 °) is smaller by a few dB. The source of this asymmetry is not yet known. The dipole pattern (Figure 10) and the phase difference (Figure 11) plots show that at 30 kHz, the probe reproduces the ideal patterns quite well. If the probe were scattering the acoustic field, it is expected that it will scatter the higher frequencies more than the lower frequencies. Since the data shows the opposite trend, acoustic scattering may not be the cause of this error. Further experimentation would be required to determine the source of the dipole pattern distortion; other possible error sources include the crosstalk as mentioned earlier.

In the future, a new intensity probe should be constructed with three fully functional sensors. The three-pressure-sensor measurement technique can then be evaluated. The new sensor should have preamps local to the sensors if the sensitivity specification allows. These preamps will reduce the crosstalk and perhaps improve the dipole patterns.

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